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14. ABSTRACT
MR and MRS SAT are now in the flight vehicle construction/integration/test phase. Constraints have been clearly defined for each subsystem and efforts have shifted to integrated component testing. Subsystem timelines have been formed and are integrated into a master schedule. In-depth research for each subsystem is being documented, and relationships with mentors from a variety of companies are continuing to flourish. Bench testing of individual components (i.e. solar arrays, communication hardware), is ongoing and has led to the integration and testing of the initial MR/MRS SAT prototypes.

The successful design, production, and launch of MR/MRS SAT will be of great value to the University of Missouri-Rolla and the aerospace community. UMR SAT students will benefit from the hands-on experience of designing and building a satellite, while the

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aerospace community will benefit from the engineering and scientific return obtained at a modest cost.

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Design, Fabrication and Test of a Formation of Two Satellites

Connected by a Tether

A Final Report Submitted to the
Air Force Office of Scientific Research
University Nanosat Program

August 3, 2007

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Introduction

A recent development in spacecraft mission design involves the increasing use of Distributed Space Systems (DSS). Several key technologies must mature sufficiently to facilitate these missions, including the use of spacecraft flying in tightly controlled formations. Such formations may be controlled using "free flying" navigation schemes, or alternatively by using tethers to constrain the formation geometry. An investigation is being conducted by the UMR SAT design team to further develop this technology using two small spacecraft flying in free formation. Although the title of this study indicates the use of a tether, the design team elected to focus on free flight and to not include a tether with this mission to simplify the scope of this student-led effort. After insertion into orbit, the spacecraft pair will be navigated to maintain a relative separation as closely as possible to that of the commanded configuration. Analysis and evaluation of the formationkeeping process can then be made so that the merits of the control approaches are available to future mission designers. In addition, a number of innovative approaches to spacecraft technology are being developed and tested including the feasibility of using wireless communications between the two satellites using off-the-shelf technologies.

The spacecraft pair is being designed, constructed, and tested by students and faculty at the University of Missouri-Rolla (UMR). The successful launch of the spacecraft will be of great value to the Air Force, NASA and UMR. The Air Force and NASA will benefit from engineering and scientific return obtained at a very modest cost. Students at UMR are benefiting from the hands-on experience of designing and building a satellite. The Air Force and NASA also have the opportunity to identify highly qualified students for possible hiring after graduation.

Since receipt of grant funding in April 2005, much progress was made. The team successfully completed four design reviews (SCR, PDR, CDR, PQR, and FCR), culminating in the final down-selecting Flight Competition Review held in Albuquerque, New Mexico March 26-27, 2007. The UMR team finished in third place (out of eleven university competitors) and was named Most Improved Team. Much of the flight hardware has been procured and assembled. However, much operational and environmental testing remain to be conducted. Some flight software is still being developed as well. Because the team was not selected to compete in the Nanosat 5 program, the UMR SAT students and PI are currently considering how to proceed with the development of the spacecraft pair. The team currently hopes to find the means to continue the development and seek a launch opportunity.

The team size was (and is) large at about fifty, with students from many majors including aerospace, mechanical, electrical, computer, and chemical engineering and computer science and mathematics. The Space Systems Engineering lab was extensively upgraded to meet the needs of completing this project. A summary of each major area of the project is detailed in the following sections. Documentation with additional details can be downloaded from the team's website at www.umr.edu/~mrsat.

Document Overview

The purpose of sections that follow is to present the current status of the UMR SAT team's MR SAT and MRS SAT spacecraft project. These sections contain an overview of the mission, along with current requirements and constraints. Also included are summaries of each of the following subsystems:

- Structure
- ADAC
- Orbit
- Propulsion
- Power
- Command and Data Handling
- Thermal
- Communication
- Ground Station
- Outreach
- Launch Vehicle
- Testing

MR SAT Overview

The UMR SAT team at the University of Missouri-Rolla (UMR), in conjunction with a number of Air Force/NASA/industry mentors, is working toward the design, construction, and launch of its first two satellites, MR SAT (Missouri-Rolla Satellite) and MRS SAT (Missouri-Rolla Second Satellite), which will fly in close formation. The goals of the UMR SAT team are to test new technologies for Distributed Space Systems missions, including the study of the dynamics of satellites flying in tightly controlled formations and the development of a low-cost wireless communication link between the satellite pair. Data obtained during the close formation flight phase will be evaluated for the benefit of future missions. As a result of the modest budget that accompanies a university level project, the UMR SAT team has used innovative, low-cost solutions to meet objectives.

The UMR SAT team was accepted into the Nanosat 4 student competition in 2005. This competition was sponsored by the Air Force, NASA, and the American Institute of Aeronautics and Astronautics. The two UMR SAT spacecraft were to be completed by the relatively short deadline of March 2007 so that they could compete against ten other universities.

The design and construction of the satellite pair was (and is) a valuable educational experience for the student team. The project provides the experience of using a team approach to solving a real-world assignment and facilitates a fundamental understanding of the spacecraft design process. The approach used in conducting this project is to emulate industry as closely as possible. In this approach, students gain an understanding of engineering ethics along with significant experience in written and oral communication. Appendix A includes an organizational chart showing the current team structure.

Mission Requirements and Constraints

Mission requirements and constraints have been defined for both spacecraft, assuming that they will be launched from the Space Shuttle. Although it is unlikely that the Space Shuttle will be used to launch the spacecraft, this assumption will ensure that the requirements are applicable to a variety of launch vehicles since the Space Shuttle has the most demanding constraints. The current mission constraints are shown below in Table 1.1.

Table 1.1 MR/MRS SAT Mission Constraints

System	Description	Requirements		
		Minimum	Goal	Achieved
Orbit	Altitude (km) Eccentricity Inclination	190 Approx. zero 39°	700 zero 56° or higher	Determined by Launch Vehicle
Operational Life	Total time in orbit	2 weeks	2 years	TBD
Structure	Shape Length (cm) Width (cm) Diameter (cm) Height (cm) Mass (kg)	Cubic ≤ 45 ≤ 45 N/A ≤ 45 ≤ 30	Design to be compatible with several commercial launchers	Hexagonal Prism N/A N/A ≤ 47 ≤ 47 ≤ 30
Communication	Satellite to ground Satellite to satellite	Data rate adequate for telemetry Custom intersatellite comm. system	Multifunctional RF transceiver Radio in 802.11b configuration	
Power	Provide electrical power throughout mission	Two week mission: Primary batteries	Longer mission: Solar cells and batteries with power regulation	
Propulsion	Cold Gas Thruster Micro Pulsed Plasma	Safe propulsion meeting requirements for the launch vehicle Technology	Full orbital and secondary attitude control of MR SAT Technology	Propulsion system designed for MR SAT orbital and attitude control. Safety still to be accepted.

<table>
<tr><td></td><td>Thruster</td><td colspan="2">demonstration</td><td colspan="2">demonstration</td><td colspan="2">μPPT undergoing testing in laboratory, design evolving.</td></tr>
<tr><td>ADAC</td><td>Determine attitude and control passively if possible</td><td colspan="2">Control of both satellites to within ±10.0°</td><td colspan="2">Control of both satellites to within ±1.0°</td><td colspan="2"></td></tr>
<tr><td>Telemetry, Tracking, and Control</td><td>Navigate spacecraft and return science and engineering data</td><td colspan="2">Control from Ground Station located at UM – Rolla</td><td colspan="2">Control from Ground Station located at UM – Rolla and other ground stations</td><td colspan="2">TBD</td></tr>
<tr><td>Thermal</td><td>Thermal control of spacecraft</td><td colspan="2">Maintain acceptable thermal limits for payload and satellite</td><td colspan="2">Passive control of thermal limits for payloads and satellite</td><td colspan="2"></td></tr>
<tr><td>Payload and Key Technologies</td><td>Payloads providing scientific and/or engineering data</td><td colspan="2">Autonomous control and relative navigation system</td><td colspan="2">Autonomous control, rel. nav. and wireless communication between spacecraft</td><td colspan="2"></td></tr>
<tr><td>Launch Vehicle</td><td>Any means by which to place spacecraft into low Earth orbit</td><td colspan="2">Any launch opportunity into low Earth orbit</td><td colspan="2">Adaptable to any launch vehicle as secondary payload</td><td colspan="2">TBD</td></tr>
<tr><td>Launch Vehicle Adaptor</td><td>Method of attaching spacecraft to launch vehicle</td><td colspan="2">To be developed to fit launch vehicle safety requirements</td><td colspan="2">Developed to fit or be easily adapted to the launch vehicles</td><td colspan="2"></td></tr>
<tr><td rowspan="6">Onboard Computer</td><td></td><td>MR SAT</td><td>MRS SAT</td><td>MR SAT</td><td>MRS SAT</td><td>MR SAT</td><td>MRS SAT</td></tr>
<tr><td>Power (W):</td><td>5</td><td>5</td><td>< 3</td><td>< 3</td><td>< 2</td><td>< 2</td></tr>
<tr><td>Memory (MB):</td><td>4</td><td>4</td><td>64</td><td>64</td><td>64 SDRAM
32 MB StrataFlash
1 MB ROM
1 CF Slot</td><td>64 SDRAM
32 MB StrataFlash
1 MB ROM
1 CF Slot</td></tr>
<tr><td>CPU:</td><td>No Processor, 4 x 8051 Micro Controllers</td><td>No Processor, 4 x 8051 Micro Controllers</td><td>386 25 MHz +, 8 x 8051 Micro Controllers</td><td>386 25 MHz +, 8 x 8051 Micro Controllers</td><td>ARM 400 MHz, 4 x 8051 Micro Controllers</td><td>ARM 400 MHz, 4 x 8051 Micro Controllers</td></tr>
<tr><td>Dimensions (cm):</td><td>25 x 20 x 3</td><td>25 x 20 x 3</td><td>8 x 6 x 2</td><td>8 x 6 x 2</td><td>9.65 x 9.14</td><td>9.65 x 9.14</td></tr>
<tr><td>Mass (kg):</td><td>0.5</td><td>0.5</td><td>< 0.5</td><td>< 0.5</td><td>0.5</td><td>0.5</td></tr>
</table>

Project Status

The following sections include a brief description of the UMR SAT team infrastructure and a summary of each subsystem and its current status. A more thorough discussion of each subsystem may be found in respective design documentation. These documents are available from the UMR SAT website at www.umr.edu/~mrsat.

Basic Infrastructure

Systems Engineering

The UMR SAT team utilizes a Chief Engineer/Program Manager approach to project management. At the highest level of project management is the Project Director, Professor Henry Pernicka. Under the Project Director are the Chief Engineer, whose primary task is to fully integrate the efforts of the entire team from an engineering design standpoint, and a Program Manager, whose task is to keep the team organized and efficient. The Program Manager currently runs a weekly team meeting where each subsystem leader briefs the team on their progress and any issues they may be facing. Prior to the weekly meeting, each subsystem lead is required to submit a subsystem progress report to the Program Manager, which includes: tasks for the previous week, tasks for the upcoming weeks, schedule and milestone status, and action items between subsystems. The Chief Engineer and Program Manager also work together to establish team goals and milestones, while assigning tasks to ensure that these objectives are met in an efficient and timely manner.

The Chief Engineer and Project Manager act collectively as a team leader. A significant responsibility of the team leadership is to ensure that the team maintains a spirit of teamwork, professionalism, and high ethical standards. The Project Manager is also in charge of establishing standards of communication, documentation, and presentation, as well as organizing design reviews and design documents.

A cadre of industry mentors also provides guidance to the project. These aerospace professionals provide input and technical assistance to the subsystems. Their review of the spacecraft design is a valuable contribution to the UMR SAT team and ensures that a viable spacecraft can be realized. The current group of mentors includes representatives from AFRL, NASA's Goddard Space Flight Center, the Jet Propulsion Laboratory, Boeing, Lockheed Martin, Ball Aerospace, Eagle-Picher, as well as other companies.

Space Systems Engineering Lab

The Space Systems Engineering (SSE) Lab at UMR is a facility dedicated to the UMR SAT team, as well as other space-related research and education. The lab is equipped with PC workstations, a clean room, workbenches, ESD safe workbenches, and tools. The two workstations, one of which features dual-processors, are equipped with software that provide programming capability, computer-aided-design, structural and thermal analysis, and systems engineering software.

The SSE lab is also equipped with a 6' x 6' x 8' clean room rated as Class 100. This clean room consists of a 6-36 vertical flow hood supported by two 3' x 6' x 8' frame members and is enclosed by vinyl strip curtains. The clean room will be used for final assembly and storage of the satellite. Included in the SSE lab are two 5' x 2.5' workbenches and some basic tools (drill, dremel tool, multimeter, etc) to use in satellite construction. Both the clean room and the workbenches are equipped with ESD wrist straps and grounding mats for use with flight hardware. An industrial grade oven has been located in the lab for use in component bake-out. A fully equipped machine shop is also readily available on campus, as needed, for assistance in the construction process.

MR SAT Web Site

The role of the website for the UMR SAT team is to display current events with the project throughout each semester. The primary function of the website is to keep mentors and contacts updated on the progress of each subsystem. The web page of each subsystem includes an overview of their responsibilities, semester goals, semester meeting times and location, and monthly updates on their progress on the satellite. The website also includes a summary of the overall mission of the project, team biographies, and pictures of satellite hardware and testing. The MR SAT website may be accessed at www.umr.edu/~mrsat.

Subsystem Summary

Structure

The Structure subsystem deals with the load-bearing body of the spacecraft. A sturdy structural design with sufficient capacity to carry all necessary components is essential to a spacecraft's mission success. It is also essential to limit the mass and size of the spacecraft in order to lower the costs associated with placing it in orbit. These primary constraints drive the overall structural design of most spacecraft. In March of 2005, the UMR SAT team was accepted into the University Nanosat 4 Competition. The constraints and requirements of this competition play a large role in the structural design.

A number of constraints have been developed for the execution of this project. These constraints include limiting total mass to less than 30 kg, and total size to dimensions within a cylindrical envelope of 47.498 cm diameter and 47.498 cm high. Additional goals include designing the two satellites to be mated prior to separation and incorporating as much commonality as possible between the two craft. The basic concept for the satellite structure (in mated formation) is shown below in Figure 1.1.

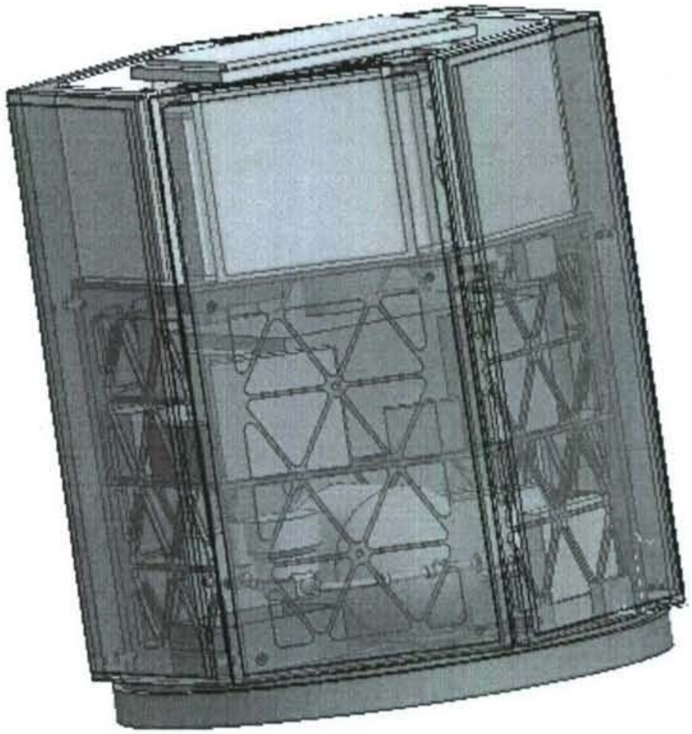

Fig. 1.1 Structural Concept for MR SAT & MRS SAT

The structure is a hexagonal prism with the upper satellite (MRS SAT) being wholly contained by the lower satellite (MR SAT). The largest and highest power consuming components are placed in MR SAT where there is more available space for solar cells and higher power generated. The structures will be mated together at launch, as seen in Fig. 1.1, and later separated when in orbit.

In designing the internal configuration, the use of only one horizontal shelf was selected to reduce the overall mass and for ease of construction. The docking mechanism is a Qwknut developed by STARSYS Research. In order to meet mission requirements, the mass and size of the satellite must be minimized while strength and stiffness are maximized. The mass of the satellite will be maintained at a manageable level due to the lightweight materials used. The relatively small dimensions used will also lead to a high stiffness.

It is also the responsibility of the Structure subsystem to verify that the structure can withstand all loads that may be applied to it over its lifespan. For this reason a number of analyses including finite element (stresses, strains), vibration effects, and thermal expansion effects are being performed.

Preliminary analyses were conducted for concept generation, and in-depth studies are now nearing completion so that the final design can be constructed. The various analyses to be completed include:

- Finite Element Analysis (stresses, strains)

- Mass Properties Analysis (masses, centroids, moments of inertia)
- Vibration Effects Analysis
- Thermal Expansion Analysis

The results of each study may require small variations in the final design in order to improve the overall mission capabilities of the spacecraft.

Testing will also be necessary to verify the results of these analyses. Before completion of the project, the spacecraft will undergo a series of tests to insure the structural integrity within the design limits and verify the results of the analyses in Section 3.4.3. Potential testing facilities are being researched. Once the spacecraft has been assembled it will be tested and subjected to all the loads it is expected to undergo throughout its operational life, with particular focus on its ascent to orbit.

Attitude Determination and Control (ADAC)

The responsibilities of the ADAC subsystem include the tasks of determining the orientation of the spacecraft along its orbit and maintaining a desired orientation to facilitate completion of the mission objectives. Attitude, or the orientation of a spacecraft, is crucial to the success of a mission. Improper determination or control of the attitude of the spacecraft can lead to catastrophic results. For example, solar cells on a spacecraft must be oriented towards the Sun; failure to maintain specific orientations would lead to depletion of the batteries. There are also potentially damaging thermal effects as well as loss of communications with the spacecraft that can arise from incorrect attitude of the spacecraft.

Maintaining proper orientation of the spacecraft will not only protect against mission failure, but it will also ensure a maximum operational life of the spacecraft. The amount of time that the spacecraft will be in range of communication with the ground station will partly determine how much data can be transferred to and from the spacecraft. However, precise control of the antennas onboard the spacecraft will facilitate the transfer of more data. The position of the antennas will most likely be controlled by the attitude of the spacecraft, so it will also be the job of the Attitude subsystem to maintain the data rate at a high level.

The mission requirements for the attitude of MR SAT and MRS SAT consists of consistently pointing the space-to-ground antenna towards Earth with an accuracy of plus or minus ten degrees, rotate 360° per orbit about the pitch axis and maximize the slew rate so orbital maneuvers can be efficiently performed during the chase sequence.

Magnetometers comprise the primary components for attitude determination, while magnetic torque coils and cold gas thrusters will be the primary components for attitude control. Research is nearing completion on the closed-loop formationkeeping controller. The flight hardware has been fabricated on campus or procured from the manufacturer and is undergoing testing at UMR. All that remains is the rigorous testing of the determination and control algorithms needed to fly in space.

Orbit

By making use of the orbital elements, such as the instantaneous position and velocity of a spacecraft, it is possible to predict the satellite's future trajectory. This method is based on the use of a set of equations of motion derived from the dynamics of the satellite. Conventional satellites can normally be accurately modeled using equations derived from the two-body problem, with the Earth and the satellite as the two spherical bodies. The orbits obtained using this two-body method can fall into one of three categories: elliptical, hyperbolic and parabolic (known as "Keplerian orbits"), each with their own characteristics and applications. These equations of motion will be relevant during the free-flying portion of MR SAT and MRS SAT's orbits. The orbit that is applicable to the free-flying portion of MR SAT's operation is that of an elliptical nature, or more precisely a near-circular orbit.

The primary method of determining the orbital elements of the MR SAT spacecraft will be through the use of the Global Positioning System (GPS). A GPS receiver onboard each satellite will be able to collect the exact position and velocity of each satellite at any given time and store it until it can be downloaded. The data received will include latitude, longitude and altitude, plus velocity magnitude and heading. It is then possible to solve for the orbital elements and determine where the satellite will be in the near future. Adjustments may have to be made to the orbit determination (OD) process to provide an accurate prediction of the orbit to allow for precise control of MR SAT, since the exact orbit of MR SAT is currently unknown because several factors have to be taken into account before its final orbit can be determined. These factors, such as launch vehicle obtained, can change the MR SAT mission significantly.

The Orbit subsystem has purchased and received two unrestricted GPS receivers from Spacequest Ltd. Spacequest is registered with ITAR and has also delivered a restricted terrestrial engineering unit to assist with spacecraft integrations and ground testing.

Propulsion

The main use of a propulsion system is to provide a means to maneuver a satellite through space. This maneuvering is typically used for changing the orbit shape and size. A secondary use for the propulsion system is to provide a means for attitude control.

Research was conducted to determine the propulsion options available to the UMR SAT team, leading to the identification of many types of propulsion systems. Most of these were not suitable for the UMR SAT team because of size, mass, budget, or power requirements; however, several promising options for propulsion were found. At this time two main design options are being pursued: a Xenon compressed gas design and a saturated liquid design using R-134a. The preferred propulsion system for MR SAT is the R-134a design. Due to the limitations of the Nanosat 4 competition, specifically the use of pressure vessels and propellants capable of phase changes, the use of R-134a requires more in depth and specific analysis and testing prior to it being accepted by AFRL. The Xenon option is being pursued and documented in this report, as a contingency design for MR SAT in the event that R-134a is not accepted and an alternate backup system needs to be incorporated. .

Construction of both of these systems is possible from off-the-shelf parts, which reduces cost and complexity. To provide containment of the Xenon propellant, a composite over-wrapped tank has been selected. Communications with the manufacturer, Carleton Technologies, Inc., have shown that this tank meets the preliminary needs for the MR SAT propulsion design. Current information is provided in Table 3. The burst pressure is 105.490 MPa. The tank is constructed of carbon/epoxy over-wrapped Aluminum liner with a thin outer fiberglass. The tank is currently designed for Department of Transportation (DOT) commercial use and meets DOT-CFFC specifications. The DOT standards are in review to determine if all design restrictions are met with this tank. While the tank exceeds the 5.0 factor of safety 3.447 MPa (500 psi) minimum burst pressure requirement, valid proof for meeting 20 G loading and vibration restrictions is still needed. For the R-134a configuration, an alternate tank, the Marotta BS25-001, has been selected and purchased to provide the necessary propellant control. An internal Propellant Management Device (PMD), consisting of filters and screens, will be integrated into this tank. The shell is manufactured with Stainless Steel 316L with the internal filters manufactured with Stainless Steel 304L/316L. The internal screens are of expanded aluminum 901A. Table 4 highlights the specifications of this tank.

For both Xenon and R-134a design configurations, the length of the tank is placed perpendicular to the z-axis of the satellite. An example of this can be seen in Figure 1.2. It is required that the tank be placed at the center of gravity of MR SAT when MRS SAT is undocked. This placement will minimize the cg movement effects on attitude determination and control as the propellant is expelled and the MR SAT mass decreases. This exact placement is being coordinated with the Structure subsystem.

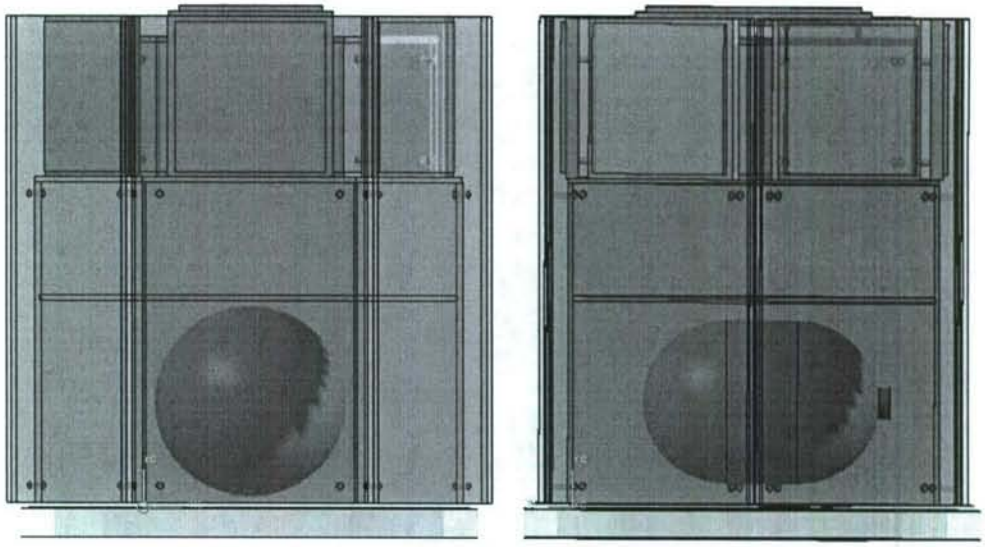

Figure 1.2 Example Propellant Location and Orientation

The operation of the thrusters will be autonomously controlled through the formationkeeping algorithm developed by the Attitude and Orbit subsystems, with the ability to command additional firings though a communication uplink.

Power

The objectives of the power system are to acquire, store, and distribute power in a way that will sustain the operations of the mission. In order to achieve these objectives, a satellite power system must consist of the following components: a power generation system, an energy storage system, a power distribution system, and a power regulation system. For the MR/MRS SAT spacecraft, the power generation system will consist of solar cells and the energy storage system will consist of secondary batteries. Each of the major components of the electrical power system is discussed in further detail in a following section.

The two satellites, MR SAT and MRS SAT, are hexagonal in shape with solar cells that will be placed on all six sides of the satellites with the possibility of placing a panel on the negative z axis side of MR SAT. The size of the panels varies based on thruster and antenna placement. The amount of power produced by the solar panels depends on several different parameters including the cell voltage, cell current, Sun incident angle, temperature and ratio of the Sun power density in space and on Earth. Batteries will be used to supply power while the satellites are in the Earth's shadow.

In the current design of the solar arrays, cells will be mounted on the body of the satellite using all available surface area. To provide a steady source of power for the mission operations while in Earth's shadow, the satellite will be equipped with a bank of secondary batteries. Acting as a power reservoir, these batteries will be recharged and must be capable of providing power during the eclipse phases of the mission, as well as during periods when the satellite power draw exceeds the power generated by the solar panels.

To lengthen the life of the batteries and enhance the function of the satellite, the power distribution electronics are designed for maximum flexibility. This flexibility helps prevent critical failure of the mission if any problems arise. The solar panels, batteries, and power distribution hardware are wired in parallel. The incoming energy from the solar panels will charge the batteries and power any operating devices on the satellite. The batteries are used to supplement the solar arrays in peak load situations, as well as provide power to the satellite during eclipse. If any one of the batteries exhibits erratic behavior, it can be isolated from the rest of the system without compromising the mission. Furthermore, the satellite can operate solely upon the solar arrays, although functions would be limited to sunlit portions of the orbit only.

The power distribution and regulation systems provide and route power to each device on the satellite. These two systems convert battery bus voltage to the voltages appropriate for each device, protect the satellite from shorts and surges, and act as the hardware component for the power regulation duties of the onboard computer.

Command and Data Handling

The onboard computer must accomplish several distinct tasks: coordinating subsystems to work together, storing and processing data from onboard sensors, running the spacecraft-to-Earth communications system, and running the communications system between both satellites. The following is a discussion of the selection process for both hardware and software components to be used onboard the satellites.

Low Earth orbit (LEO) satellites experience radiation bombardment as well as intermittent high level bursts of radiation not routinely experienced on Earth. This radiation can interfere with or even permanently damage electronic equipment. This requires that all electronic equipment be shielded to some degree to ensure error-free operation. Due to size and mass constraints, shielding may often be less than desired. Therefore, electronics systems, more specifically the onboard computer, microcontrollers, and radio equipment must be able to cope with and protect against the effects of radiation. Radiation has two distinct effects on the electronic systems. The more catastrophic of the two is failure of an electronic component or even the entire system. This severity of failure is uncommon in LEO and, therefore, protection is focused on the second effect. This second, less severe, type of interference can manifest itself in the form of single event upsets (SEU) or single event latchups (SEL). Radiation bursts can cause a reversal of a bit or even sections of data within the processor, memory, or bus. Radiation hardened processors, which can detect and correct these errors, can be used in space applications; however, these are typically out of the price range of university design teams.

Power usage is a concern for any satellite and an onboard computer potentially can be a large user of that energy. Due to the size of MR SAT and MRS SAT, there is limited space for solar cells and since each subsystem must share, power usage by each piece of hardware must be minimized.

The workload of the onboard computer will be divided into high-level and low-level classes. The low-level processing will be concerned with controlling the closed-loop type processes associated with each subsystem. Small 8051 microcontrollers will relay the relevant information to a central processor that will be responsible for central data storage, system maintenance, and any relatively intense computations which may be necessary including possible camera operation, the GPS unit, and all input or output with the memory. The central processor will also be responsible for operating both the MR SAT to ground and MR SAT to MRS SAT communication equipment. The microcontrollers will interface with the hardware of certain subsystems which require constant attention and will provide an easier interface for the processor to control those subsystems. The onboard computer will have the ability to send each microcontroller a standardized format message which directs the microcontroller what to do, allowing the computer to move on to other tasks.

The software onboard MR SAT and MRS SAT will be responsible for controlling communication devices, subsystem data collection, power regulation, and basic automation commands. The software will fall under two basic categories: code for the 8051 microprocessors that interfaces with the various subsystems and code for the central processor for data storage and high-level processing.

Most sensor hardware has been procured and initial testing has been completed. Currently, the interface hardware that bridges the sensors to the computer is being developed. Software has been implemented on both the computer and microcontroller boards to read the sensor information but further integration is still required.

Thermal

The goal of the thermal subsystem is to implement hybrid control of the thermal limits for both satellites and their payloads. The satellite equilibrium temperature is governed by radiation and internal heat dissipation. Convection is not considered for the satellites. The temperature can be controlled, within limits, by using heat sinks and insulation. By connecting the components of the satellite using conduction pathways, a nearly uniform temperature can be maintained within both satellites. Conduction from the element depends on the heat transfer coefficient of the material and contact pressure, and can be used to effectively transfer heat throughout each satellite.

The objectives of the thermal subsystem are to analyze the satellite thermally, determine the safe working temperature range for the orbit specified, and to utilize methods that will ensure the thermal safety of the satellites over large temperature ranges. Temperature measuring sensors will also be installed, tested and integrated into both satellites.

Convection can be ignored in space; unless pressured modules or fluid loops are used since convection is transfer of heat through a fluid (molecules in space are too sparse to transfer significant heat). Nodes for the thermal analysis are governed by type and size of mesh applied for the analysis. After the completion of the steady-state thermal analysis, a transient-state analysis will be conducted to enhance accuracy of the results obtained from the steady-state analysis.

The design strategy was to concentrate on minimizing the effects of thermal deformations and stresses. This includes enclosing critical members in insulation to keep temperature gradients low, accounting for friction in sliding joints, using structural members with low coefficients of thermal expansion (CTE), designing joints that connect members of different materials, using materials with high thermal conductivity, and determining how temperature affects the strength of composite materials. A catalog of the thermal properties of each material used on the satellites was made. Batteries have a very small operating range which makes them the most critical component for thermal control. Hence, the batteries will govern the allowable ranges for satellite temperature variation.

The effects of the beta angle were determined by using orbits at different altitudes and orientation and studying differences in total heat or irradiation due to different sources such as the Sun, Earth, and albedo. There are numerous thermal control methods being studied for possible applications to the project. These include the use of conductive links or to short all the parts of the satellite, black paints on the electronic boxes, FOSR radiators, conductive pastes, insulation, cooling system, and instruments that switch on when the satellite becomes too hot or too cold. Temperature sensors will be required for the batteries, solar panels, and CPU.

Electronic components will be tested for functionality through low pressure and over a wide range of temperatures in an effort to identify any faulty hardware. Thermal barrier materials will be tested to determine what and how much will be used in the final design. The thermal sensing equipment will require calibration to ensure accurate readings. The final design will also be subjected to the thermal environment it is expected to endure on orbit. Effects of spin rate and orbital decay on the temperature of the satellite will be analyzed.

The responsibilities of the Thermal subsystem during operation include temperature monitoring and control. Temperature transducers will read the temperature variations of vital components while the satellite is in orbit. The onboard computer will analyze the data to insure the satellite remains in its safe ranges and will store and send data to the ground station for further analysis.

Communication

The communication system is necessary to relay information from the ground station to MR SAT and from MR SAT to MRS SAT. The communication link between the ground station and MR SAT is used to transmit commands and receive data collected in space. Because the MR SAT project will be composed of two separate spacecraft, a second communication link is required to connect the pair.

The space-to-ground communication system onboard MR SAT is composed of a transmitter, a receiver, and two antennas. In order to reduce the complexity of the entire system, different antennas will be used for reception and transmission. The entire space-to-ground communication system uses frequencies in the UHF/VHF Band (approximately 140 - 460 MHz). On Earth, amateur radio equipment run by the UMR Amateur Radio Club will be utilized for communication from the campus ground station to MR SAT.

The inter-satellite communication system will be based on commercial off-the-shelf, low-cost wireless technologies. Selected transmitters and receivers will rely on Bluetooth technology and commercial non-space-rated equipment has been selected. In order to protect these products, they will be upgraded with radiation shielding; however, antennas will need to endure the harsh space environment (vacuum and very high temperature gradients), as they will be deployed outside the spacecraft. Thus, commercial non-space-rated antennas cannot be selected, and space-rated antennas are being built on campus.

Given the tight size constraints for the entire satellites and the antenna type chosen, it is necessary to utilize a deployment mechanism. This mechanism should be reliable, compact, and cost effective. The best mechanism to meet these criteria is a tape measure style antenna. The antenna is a flat piece of metal that is rolled up around a cylinder during launch. Once the satellite has been deployed, the antenna is unrolled to full length, at which point communication with the satellite is possible. This same mechanism will be used for both the transmitter and receiver antennas.

At this time, space-to-ground communication components have been selected. The UHF/VHF communication system will be used for MR SAT. This system has been purchased from Hamtronics and Spacequest and consists of a Hamtronics UHF transmitter and a Spacequest RX-145 VHF receiver. The inter-satellite communication system has been designed and two Bluetooth units were purchased. The testing process has recently commenced and its evolution will be closely related to the C&DH subsystem's implementation of subroutines. The next steps are to complete the integration process of the entire system into the structure of the satellite and to prepare an intense testing process of the global package (onboard computer and wireless communication devices) to verify the robustness of the system.

Ground Station

The goal of the Ground Station subsystem is to develop and integrate ground station equipment into the MR SAT system. Communication with MR SAT is essential to the success of the mission. It is for this reason that a ground station must be established at UMR. The ground station must have several components in order to properly perform its duties. These include a transmitter, receiver, antenna, and modem which are currently being researched for purchase at UMR.

Outreach

The goal of the Outreach subsystem is to promote the field of Astronautics to students of all grade levels and to inform the public about the efforts and accomplishments of the MR SAT team and the Nanosat Program.

Development of the Outreach program has been accomplished by teaming with the UMR Miners In Space Team as well as the University's outreach programs. Not only does the team desire to educate future engineers, but also to interact with them. Efforts are being made to provide meaningful cooperation with high school level education programs to have student interaction with either their programs or the MR SAT team project. A prime example of this is the CASA program (http://teachers.columbia.k12.mo.us/hhs/fthompso/casa/) at Hickman HS in Columbia, Missouri, in which UMR students work with teachers and students to simulate a week-long space mission.

Future program development is being made in the following areas:

1. Continuing development of educational presentations to all grade levels
2. More involvement in the CASA program and similar programs
3. Finding or creating more programs at the high school level in surrounding communities
4. Developing a program that allows high school students to be involved in the MR SAT Design Team
5. Creating an online, possibly interactive, outreach website that can educate students nation wide; perhaps becoming part of teachers' lesson plans

Launch Vehicle

The responsibilities of the Launch Vehicle subsystem are focused on the successful mating of MR SAT with the Lightband separation system. The mechanical and electrical interfaces must be designed such that the satellite can survive the severe vibro-acoustic and shock environment associated with launch operations, while transmitting vital telemetry data to the ground station. Secondary responsibilities of the subsystem include ensuring that the satellite can be handled by ground support equipment and facilities in preparation for final mating before launch. The satellite itself must be able to be handled by support equipment at UMR, AFRL, and anywhere else that might be required.

With the UMR SAT team being accepted to the Nanosat 4 competition, more extensive research was conducted by the Launch Vehicle subsystem. An extensive list of current launch vehicles was compiled, along with contact information for each respective company. The Launch Vehicle subsystem has also been researching launch vehicle adaptors. Most launch vehicles provide their own adaptors; however, in the event that the final launch vehicle does not provide an adaptor, extensive research is being conducted on the Lightband Separation System.

The Launch Vehicle subsystem is analyzing the safety concerns in the general sense of the overall satellite: to ensure it will be safe to fly as a secondary payload. Safety is very important especially when testing some of the new technologies that the team is researching. Now that extensive component and subsystem testing is underway and the prototype testing has started, safety to MR SAT and the team members is of the highest priority.

Mission constraints applicable to the launch vehicle subsystem state that the satellite must be able to mate with the Lightband Separation System. The exact format of the mating plane was heavily dependent on the structure of MR SAT. Selection of the hexagonal shape of the satellite meant that the satellite footprint would not sufficiently cover the Lightband ring such that all mating bolts could be utilized; thus, an adapter ring was designed so that the 24 Lightband bolts could all be used to mate the satellite to the separation ring.

The electrical constraints are derived primarily from the Nanosat User's Guide, Section 6.2.3, and the specifications of the Lightband ring itself. Two or four 15-pin electrical connectors will be used in conjunction with two or four separation microswitches to relay all relevant telemetry data to ground crews during launch.

Additionally, the User's Guide requires a system to support ground handling operations both at the university level and at the launch vehicle integration site. A system was developed to lift the satellite vertically, and if necessary, rotate it 90 degrees to a horizontal position and continue to carry it in that position until mated with the launch vehicle.

Currently, the main goal of the Launch Vehicle subsystem is to ensure that both spacecraft can be successfully integrated and that the spacecraft will be able to be certified for spaceflight. The ground support equipment is the main area of work in progress for this subsystem.

Testing

The Testing subsystem oversees all of the testing plans as well as actual testing at the component level, subsystem level, and system level. This includes the prototype testing as well as the flight model testing. When a test is conducted, a testing log sheet is completed with details about that test. The Testing subsystem then takes the testing logs and compiles them into an overall testing log. Types of testing include vibration, thermal, electromagnetic, acoustic, radiation, vacuum, and various other component specific tests.

Documentation

The goal of the Documentation System is to establish a Configuration Management process which successfully organizes and correlates all documents from each subsystem. To achieve this goal, a process for creating, cataloging, storing and updating documents was established. Every document created for use by anyone on the UMR SAT team has four pages preceding each document. The first four pages consist of a title page, a revision history page, a document author contact page and a table of contents. From this point forward the individual creating the document has the freedom to compose text in most any professional format they deem necessary. However, they must have page numbers listed on all pages; excluding the title page. A recent development was the transfer of the team's documentation into a web-based Wiki system that facilitates improved document access and updating.

Conclusion

MR and MRS SAT are now in the flight vehicle construction/integration/test phase. Constraints have been clearly defined for each subsystem and efforts have shifted to integrated component testing. Subsystem timelines have been formed and are integrated into a master schedule. In-depth research for each subsystem is being documented, and relationships with mentors from a variety of companies are continuing to flourish. Bench testing of individual components (i.e. solar arrays, communication hardware), is ongoing and has led to the integration and testing of the initial MR/MRS SAT prototypes.

The successful design, production, and launch of MR/MRS SAT will be of great value to the University of Missouri-Rolla and the aerospace community. UMR SAT students will benefit from the hands-on experience of designing and building a satellite, while the aerospace community will benefit from the engineering and scientific return obtained at a modest cost. Further information regarding MR SAT can be obtained by contacting the Project Director, Professor Henry Pernicka, at (573) 341-6749 or pernicka@umr.edu.

Appendix A: MR SAT Organizational Chart